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Review of Ultrasound Performance From 5 to 20 MHz on an Aluminum Standard

by Raymond E. Brennan and James M. Sands

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14. ABSTRACT

An ultrasound system has been set up for nondestructive evaluation of armor tiles and composite systems. Critical system components including an internal pulser-receiver and digitizer board, a stepper motor indexer board, a four-axis scanning frame, an additional two-axis controller, a central processing unit with integrated software package, an immersion tank, and a series of ultrasonic transducers are described in detail. Characteristics and parameters of the various transducers are summarized. Operation of the equipment and utilization of various software tools are detailed to provide a basic method for conducting ultrasound C-scan imaging and analysis. This method is applied to experimental characterization of a standard, which is important for verifying system and transducer parameters as well as exploring system capabilities and limitations. A full system evaluation citing these specific capabilities and limitations is discussed.

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1. Introduction

A comprehensive ultrasound system has been set up in Laboratory L1088 of the U.S. Army Research Laboratory (ARL) for nondestructive evaluation (NDE) and characterization of various armor tiles and armor systems. The unit will serve as a critical NDE component to complement the x-ray computed tomography (XCT) capabilities that are currently in place. This report outlines the abilities and limitations of the ultrasound system, provides details of key parameters involved in the system setup, and summarizes a procedure for operation of the equipment.

2. Equipment Description

The ultrasound system consists of eight major components including an internal pulser-receiver and digitizer board, a stepper motor indexer board, a 4-axis scanning frame, an additional 2-axis controller, an immersion tank, various ultrasonic transducers, and a central processing unit (CPU) with an ultrasound software package for integrating and controlling the unit (figure 1). The ultrasonic transducer is the central component of the system while the rest of the equipment is used to perform functions that relate directly to its operation. Some of these tasks include supplying initial energy to the transducer, collecting and amplifying signals detected by the transducer, providing mechanical positioning and manipulation of the transducer, and displaying and converting the collected signals into a usable format for interpretation. While a transducer, in general, is a device that converts one form of energy into another, an ultrasonic transducer specifically uses a piezoelectric component to convert electrical energy in the form of an initial pulse into mechanical energy in the form of vibrations. This results in the generation of an acoustic wave at a specified frequency which interacts with the material under analysis. The acoustic impedance differences between the immersing medium and the sample or between the sample and any material inhomogeneities result in reflection of the acoustic waves at these boundaries. The reflected signals are collected by the transducer and re-converted from mechanical waves into electrical signals that are interpreted for nondestructive evaluation of the test material. In order to improve the acoustic impedance match between the transducer and enhance the amount of ultrasound energy that is transmitted into the test material, an acoustic medium of water is often utilized. For this purpose, a large immersion tank capable of handling materials as large as 20 × 20 in and as thick as 20 in is set up to contain the water.

The roles of the pulser-receiver, digitizer, motion controllers, CPU, and software are described in relation to operation of the ultrasonic transducer and collection of acoustic signals. The combined pulser-receiver/digitizer board is an external analog-to-digital internal pulser-receiver 12-bit unit (AD-IPR-1210) that is connected to one of the peripheral component interconnect

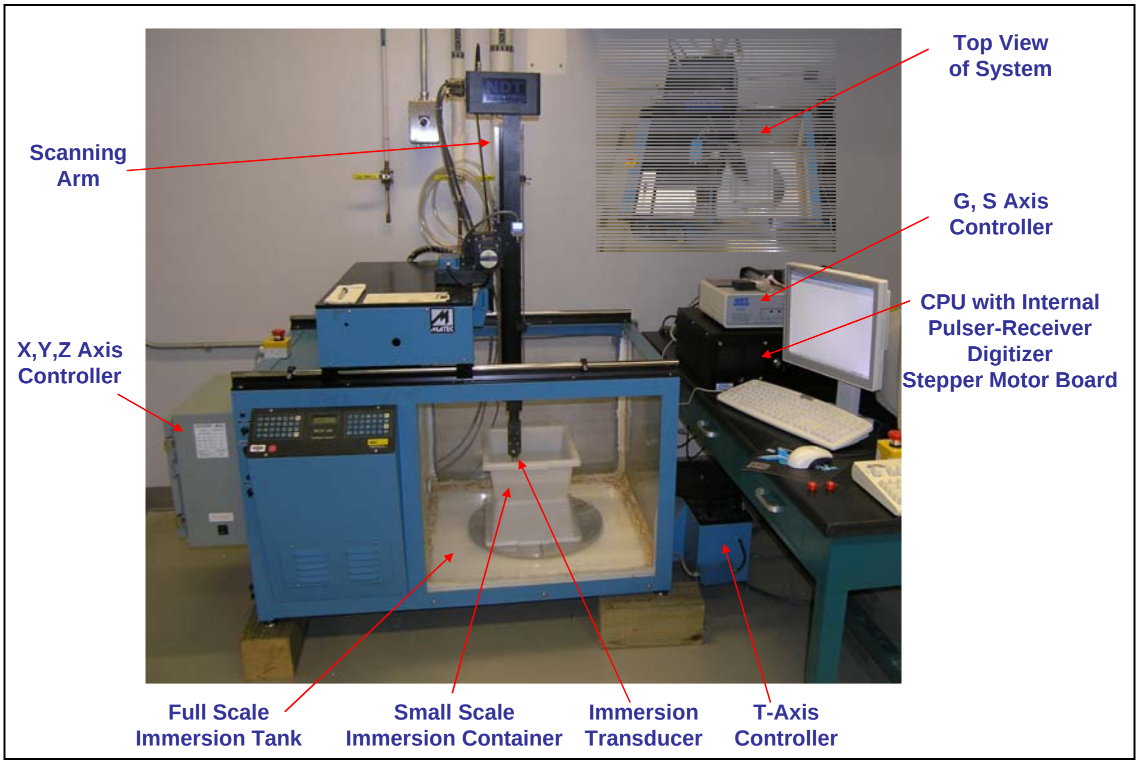


Figure 1. Ultrasound system equipment.

(PCI) slots of the CPU. The pulser-receiver component of the board is used to send the initial electrical pulse to the transducer which generates the ultrasound waves. This unit also collects and amplifies the reflected ultrasound signals in the form of analog data. The digitizer component of the board is used to convert the raw analog signal data from the pulser-receiver into a digital format that can be directly interpreted by the software. Some of the specific features of the AD-IPR-1210 card include high-voltage negative spike pulsing of 300 V standard and 400 V optional, adjustable pulse width from 100 ns to 10 μs, pulse-repetition rates from 0.1 to 10,000 pulses per second, 0.5–30 MHz bandwidth, a gain range of –20 to +80 dB, and a 100-MSample/second sampling rate. These parameters make the system ideal for handling ultrasonic transducers with frequencies up to 20 MHz.

Up to this point, only ultrasound signal related issues have been discussed. Another key component for performing ultrasound imaging is the mechanical manipulation of the transducer to control positioning and motion. A 4-axis scanning frame is fitted to the immersion tank for control of the x, y, z, and t (translation) axes (figure 2). The ultrasonic transducer is attached to a mechanical arm that is translated in the x, y, and z directions while the bottom of the immersion tank contains a rotating circular table through which translation can be controlled. In addition, the mechanical arm is fitted with a counter-rotating pulley system for manipulation of the tilt and rotation of the transducer. The tilt is controlled by the g, or gimbal axis, while the rotation is controlled by the s, or swivel axis, making a total of 6 axes that control the x, y, z, t, g, and s directions (figure 2). The g and s axes are controlled by a 2-axis external box, the x, y, z, and t

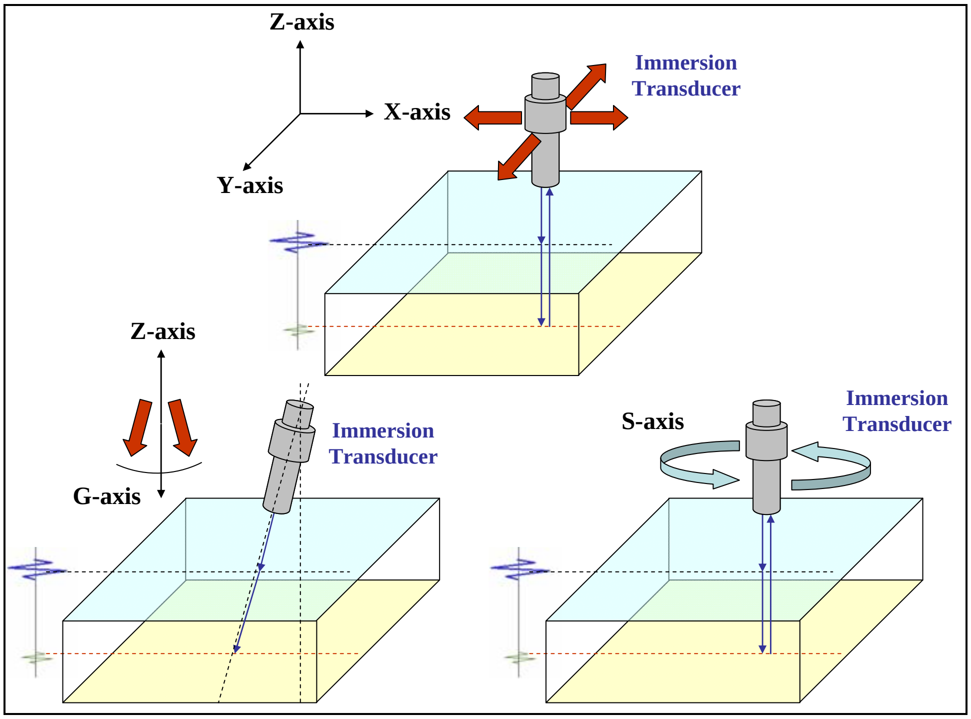


Figure 2. Schematics of X, Y, Z, T, G, and S axes.

axes are controlled by the 4-axis scanning frame, and both of these units are input to a stepper motor indexer board (SMC8-PCI) that is connected to one of the PCI slots of the CPU. While the SMC8-PCI board is capable of driving up to eight independent channels, only six are used in this case, one for each axis.

With the ultrasound signal and 6-axis control capabilities integrated into the CPU, the next major component is a suitable software package that enables the system to generate useful ultrasound data. The software that is used for this purpose is a program called UltraWin* Version 2.83. Some of the software capabilities include multiple pulser/receiver and analog-to-digital converter support through the AD-IPR-1210 board, 6-axis motion control support through the SMC8-PCI board, real time display and acquisition of A-, B-, and C-scans, up to two gate settings, RF waveform storage and replay, cluster analysis, and three-dimensional (3-D) C-scan imaging. The aforementioned A-, B-, and C-scans are different methods for displaying ultrasound signal information. The first and most common is the A-scan, or amplitude scan, which displays the intensity of the received ultrasound signals as a function of time. This type of data can be collected by conducting point analysis of a specimen at any given position. The B-scan is a cross-sectional profile view of the test specimen. In this scan mode, the A-scan results are collected over either the x or the y dimension of the sample, and ultrasonic data representative of the cross-section of the selected area is displayed. In the final type of ultrasound display, the transducer moves in raster-like fashion so both x and y coordinates are collected in addition to

*UltraWin is a registered trademark of NDT Automation, Princeton Junction, NJ.

the reflected signals. A time gate is set to consider only signals within the chosen range, and this produces a two-dimensional top view of defect response, referred to as a C-scan. The C-scan is another name for the ultrasound image map, and is used to locate flaws and defects within a specimen based on acoustic differences.

The following section will describe the procedure for utilizing the ultrasound system to perform analysis on a test sample and include a description of the important parameters used to extract valuable ultrasound data.

3. Ultrasound System Procedure and Parameters

There are two components of the procedure that will be described for analysis of an armor ceramic plate test sample including a description of the physical setup of the sample and a description of the UltraWin test parameters and scan execution. In terms of the physical setup, the immersion tank is filled, preferably with higher purity deionized or distilled water as the acoustic medium to minimize the presence of particulates that could potentially interfere with the integrity of the data collection. The tank is filled to a suitable level to account for the thickness of the test specimen and the desired water path between the transducer and the specimen. Next, the armor ceramic test plate is immersed in the tank. After immersion, air bubbles that form on any sample surfaces are removed to avoid interference with the relevant sample data collection. In general, it may also be advantageous to use small parallel plates or slides of the same thickness to prop the test specimen above the bottom floor of the tank. This can often provide a greater acoustic impedance mismatch between the sample and its contacting medium which may enhance the strength of the bottom surface reflected signals. Some characteristics of an ideal specimen for ultrasound testing include two flat, parallel top and bottom surfaces and minimal surface roughness. While these are not requirements for performing ultrasound characterization, they provide ideal conditions for analysis.

In addition to sample setup, the transducer must also be selected and attached to the end of the scanning arm. There are many types of transducers in-house, but the ones that will be briefly described are the newest set from the most recent purchase from Olympus NDT (table 1). The majority of these transducers are focused longitudinal immersion transducers with standard active ultrahigh frequency (UHF) top-mounted connections for attachment to the scanning arm. The transducers that are compatible with the current ultrasound system setup have frequencies of 0.5, 1, 2.25, 3.5, 5, 10, 15, and 20 MHz. While higher frequency transducers were also purchased at frequencies of 25, 50, and 100 MHz, these could not be used due to the AD-IPR-1210 limitations. For these focused transducers, the element sizes range from 0.25 to 1 in while the focal lengths range from 1.65 to 8.5 in. There are also two main types of transducers including Accuscan, or narrowband, and Videoscan, or broadband, transducers. Once the desired transducer is selected, the active UHF connection is screwed into the bottom of the

Table 1. Ultrasound transducers and parameters.

Transducer	Type	Frequency (MHz)	Focal Length (in)	Element Size (in)
A301S	A	0.5	1.65	1.0
V301	V	0.5	1.65	1.0
A302S	A	1.0	3.35	1.0
V302	V	1.0	3.35	1.0
A304S	A	2.25	7.00	1.0
V304	V	2.25	7.00	1.0
A380S	A	3.5	8.50	1.0
V380	V	3.5	8.50	1.0
A307S	A	5.0	8.50	1.0
V307	A	5.0	8.50	1.0
A315S	A	10.0	6.45	0.75
V315	V	10.0	6.45	0.75
A319S	A	15.0	6.45	0.50
V319	V	15.0	6.45	0.50
V317	V	20.0	4.20	0.25
V324	V	25.0	5.25	0.25
V358	V	50.0	Unfocused	0.25
V30007	V	100.0	0.75	0.25

scanning arm. After completing the physical setup, the UltraWin parameters are set up for conducting ultrasound analysis.

The first set of critical parameters is the hardware configuration which ensures that the AD-IPR-1210 and SMC8-PCI boards are communicating properly with the UltraWin software. The general hardware configuration including motor type, encoder ratio, acceleration rate, and jog speed for each of the six axes is shown in table 2. The board configuration for Channel 1 is set to IPR-90 for the pulser-receiver, AD-IPR-1210 for the digitizer, and SMC-PCI for the stepper motor board. For compatibility with the motion controllers, the scanner parameters including pitch, steps per revolution, and gear ratio for each of the six axes is shown in table 2. The advanced settings are set at encoders unused, linear acceleration/deceleration, acceleration /deceleration jog stop mode, 5-μs step clock pulse width, limit switch unused, 0.10% start speed, and 30.0 maximum speed limit for all axes. After setting up all of the hardware parameters, the A-scan parameters specific to the test specimen and transducer conditions are determined.

The amplitude scan (A-scan) displays a series of reflected ultrasound signals from the test sample and is plotted on a graph of voltage in mV along the y-axis and time in μs along the x-axis. Figure 3 shows an A-scan for a typical alumina (Al_2O_3) AD-995 ceramic plate. The position of the transducer is set by using the jog function to control the x, y, z, t, g, and s positions of the transducer. The transducer is immersed in the water by controlling the z-axis to place it at the desired focal distance from the test sample. Just as it was mentioned for sample

Table 2. General hardware configuration and scanner parameters for ultrasound system.

Axis	Motor Type	Encoder Ratio	Acceleration Rate	Jog Speed (in/s)	Pitch (in/s)	Steps Per Revolution	Gear Ratio
X	Internal	1.0	15	2.0	0.2	500	1.00
Y	Internal	1.0	15	2.0	0.5	1000	1.00
Z	Internal	4.0	10	1.0	6.0	500	0.05
T	Internal	1.0	50	30.0	62.5	1000	0.20
G	Internal	4.0	60	20.0	360.0	80,000	2.78
S	Internal	4.0	60	20.0	360.0	80,000	2.78

immersion, it is important to remove any air bubbles that may have formed on the face of the transducer. The x and y positions are jogged until the transducer is placed over the desired sample area. The g and s parameters are fine-tuned to ensure that the transducer is perpendicular to the top surface of the sample in order to maximize the ultrasound signal intensity. The jog function is also used to program the starting position in x, y, z, t, g, and s before performing an ultrasound scan.

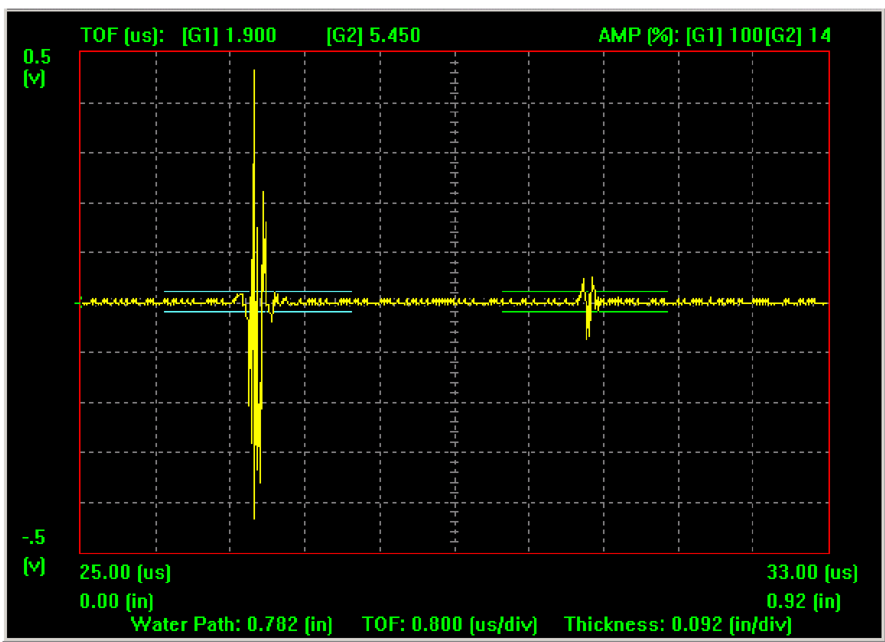


Figure 3. A-scan of 20-mm-thick AD-995 alumina ceramic.

To locate the reflected ultrasound signals from the test specimen at the current position, the analog-to-digital (A/D) function is selected (figure 4). The delay is set to 0.0 μs and the width expanded to 50.0 μs to locate the reflected signals. When the ultrasound signals from the sample are found, the delay and width are adjusted to hone in on the desired signals, most likely the top surface and bottom surface reflected signals as shown in figure 3. Other parameters in the A/D

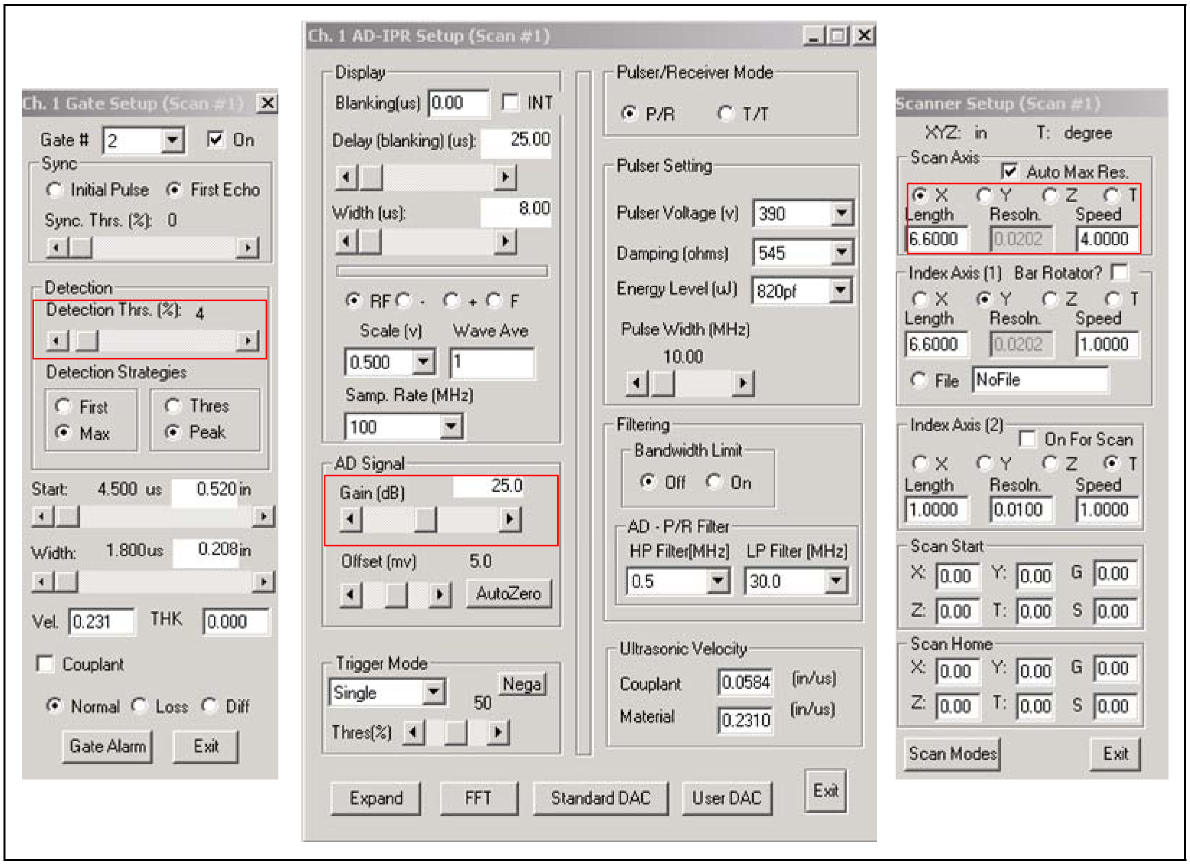


Figure 4. Screenshots of typical A/D, gate, and scanner parameters.

function are typically set as RF to display the full signal, P/R for pulser-receiver mode, a sampling rate of 100 MHz, a pulser voltage of 390 V, damping of 545 ohms, and an energy level of 820 μJ. Some of the parameters that are often varied are the voltage scale between 0.125 and 0.500 V, wave average between 1 and 20, and gain between 20 and 40 dB, depending on the amount of noise. For a combined transducer and sample interaction with minimal noise, the voltage is set as 0.500 V with an average of 1 and a gain between 20 and 30 dB. If there is a high degree of noise, this might be changed to 0.125 with an average between 5 and 10 and a gain between 30 and 40 dB. This must be optimized on a case-by-case basis depending on the signal-to-noise ratio. The gain control is highlighted in figure 4 under the AD-IPR setup window. Another option in the A/D function is to obtain a fast fourier transform (FFT) of the selected signals. As opposed to the standard method of subtracting the distance between reflected signals to measure the time-of-flight (TOF), or travel time of the ultrasound signal through the sample, the FFT analysis can be performed as a cross-correlational measurement of TOF. However, the FFT method may result in large variations due to its sensitive nature, so both methods should be employed to accurately measure TOF.

Two more critical A-scan functions that must be established before performing ultrasound imaging include gates and scan parameters. Under gates, the gated regions are set up to define

the positions of the desired reflected ultrasound signals (figure 4). A common practice is to set gate 1 to account for the top surface reflected signal and gate 2 to account for the bottom surface reflected signal. Gate 2 can also be set for the region between the top and bottom surface reflected signals for a bulk scan that is used to detect small peaks directly from material inhomogeneities within the sample, but these are often difficult to conduct unless the features are of a significantly large size. For each gate, the detection threshold is set as a horizontal line below which the signal data will not be collected. This is designed to reduce the effect of noise in a scanned image, and is compatible with the max and peak detection strategies for collecting data from the maximum peak over the desired gate. The detection threshold is often chosen as 1% if it is desirable to detect peaks from small inhomogeneities close to the noise floor, 3% for an intermediate range, or 5% if the goal is to capture high intensity signals while eliminating the effect of noise from electrical signal interference. While 1% is ideal for comprehensive sample evaluation, it is more likely that noise from signal interference will be included in the data since the threshold is set so close to the noise floor. The detection threshold is highlighted in the Gate Setup module in figure 4. It is often desirable to run scans under different gating conditions to account for every possibility. The start and width of the gate are used to set the position and range for each gate, while the normal option is used to collect data from a single gate and the difference option is used to collect data which is measured as the difference between gate 1 and gate 2. For a TOF evaluation, the Difference option is most useful as TOF2 – TOF1 determines the TOF difference at each point. The difference option is also used to describe the amplitude (AMP) of gate 1 divided by the AMP of gate 2. Again, it is useful to collect both normal and difference data in most cases. While setting the gates, it is important to use the jog function to look for any peak shifting that may occur due to thickness variations, nonparallel surfaces, or improperly calibrated positioning of the immersion tank or transducer that may cause unwanted tilt. If shifting does occur, the gates need to be widened so that the signal remains within its confines and all of the data can be collected over the entire sample area.

The scan function is important for choosing the scan area and the desired resolution (figure 4). The scan axis is defined as the axis over which the majority of motion is occurring, in most cases the x-axis, while the index axis is defined as the axis over which there is minimal motion, in most cases the y-axis. These are the two axes that are in use to define the scan and should be set accordingly. The length in inches of the scan in each of these directions is set. For a 4- × 4-in armor ceramic test plate, typical settings are 4.5 inches in each direction so that the entire sample area can be covered. The speed is set, typically at around 4.0 in the scan axis direction and 1.0 in the index axis direction in which there is minimal motion. The resolution is often chosen as the Automatic Maximum Resolution over the scan area, as set by the software according to the scan area. The length, resolution, and speed of the scan axis, in this case the x-axis, are highlighted in the Scanner Setup module in figure 4. For a setting of 4.5 in of scanning length and width, this results in an automated maximum resolution of 0.0098, which translates to a pixel size of ~249 μm. While it is often desirable to increase this resolution, especially at higher frequencies, the automatic maximum resolution setting is dictated by the size of the scan area. Manual

reduction of the resolution settings below the automated value results in glitches and processing errors in the resulting scan including offset lines and erroneous scan data. Due to these automated settings, smaller samples benefit with much higher resolution capabilities compared to larger samples.

Once the A-scan parameters are set, the C-scan function is selected to construct the ultrasound image. As opposed to an A-scan evaluation for a single point, a C-scan is a collection of data points, typically based on changes in reflected signal amplitude or TOF values. The gated regions confine the top and bottom surface reflected peaks, and the values from these gates are measured in terms of reflected signal intensity for AMP in mV and time difference in μs for TOF. The AMP values can also be directly converted into attenuation, α, or signal loss, using the equation $\alpha = 20 \log \text{AMP}$. After setting these parameters, each individual A-scan generates a single value of TOF or AMP and the C-scan image maps these data at each x and y position. A color scale is used to display the different values over the maximum range so that high and low AMP and TOF features and regions can be identified. After selecting the C-scan function, the acquire tab is used to set the map options. C-scan TOF and C-scan AMP data can be saved while scanning, the map can be magnified, the display options can be set for gate 1 TOF, gate 1 AMP, gate 2 TOF, or gate 2 AMP while running the scan, and the ranges for TOF in μs and attenuation in dB can be set. The radio frequency (RF) mode can also be selected before running the scan. This option allows not only the C-scan image data to be saved, but also saves each corresponding A-scan at each point over which the data was collected. Once the parameters are finalized, the go button initializes the scan. The scanning arm translates the ultrasonic transducer to the starting point and begins rastering over the sample at the desired speed and positions until the entire area is covered. The result is a C-scan image that can be qualitatively analyzed before performing post-processing.

The post-processing menu is opened by selecting the Replay function, which displays the selected C-Scan image. Under the Process tab, the image is selected for gate 1 TOF, gate 1 AMP, gate 2 TOF, or gate 2 AMP, and only one of these images can be viewed at a time. The scale and rulers are also displayed. Options for zooming in on specific sample areas are also displayed. However, the μs scale values for TOF images and the dB scale values for AMP images cannot be changed. The Image Filter tab fills in any missing data points by averaging the values of its nearest neighbors. The 3-D view provides a unique three-dimensional display of the AMP or TOF data that can be re-scaled and rotated in the x, y, and z directions. This is not only a good visual tool, especially for test samples with pronounced inhomogeneities, but can prove useful for observing variations from angles that were previously difficult to access. Another display option is B-scan imaging, which is also very useful for viewing a cross-sectional slice through the C-scan image. This serves as a collection of A-scan data over a selected horizontal or vertical line across the C-scan image, and is good for observing a side view by digitally slicing through the sample and looking for TOF and AMP variations. The horizontal and vertical lines can be positioned over the C-scan image to evaluate the desired regions.

The cluster tab includes the quantitative analysis options for the C-scan image. Analysis is conducted by choosing the lower and upper threshold percentage of data for evaluation, selecting the minimum pixel size of the clustered area, and selecting the minimum number of pixels contained in each cluster. When the analysis is performed, the cluster data are displayed in terms of number of pixels, total cluster area, percent area, cluster position, and peak amplitude of the cluster region. The numbered clusters can also be overlaid directly onto the C-scan image map. This is the extent of direct quantitative analysis that is available. While there is an option to convert some of the raw scan data into XLS format for use with Microsoft Excel,[*] this is extremely limited to a maximum number of 254 data points, which is miniscule in comparison to the tens and hundreds of thousands of data points that are collected for typical C-scan images. The number of collected data points increase as the resolution is increased, which is vital for high frequency scans and detection of features and inhomogeneities, and also increase with sample size. The limit of 254 is based on the column limit of data in Excel, and the small value renders the conversion of data to be relatively useless. The raw data is also encoded by the software and there is no apparent way to access the C-scan data which is vital for proper quantitative analysis. With access to the raw data, the values could at least be evaluated using a different software package such as SigmaPlot[†] or Origin,[‡] but the UltraWin software does not allow for this access and this serves as one of its most severe limitations.

4. Ultrasound System Capabilities and Limitations

The ultrasound system is fully operational and is being used for evaluation of both undamaged and damaged armor ceramic plates and armor systems. By working with the system extensively, many of the capabilities and limitations have been identified. On the positive side, the system works well as a fully integrated unit, with the boards communicating well with the software. The ability to have full control over six axes is phenomenal, in that most ultrasound systems are limited to control of only the x and y axes and possibly the z axis. The parameter settings provide a great deal of flexibility for conducting a variety of scans that enable comprehensive study of the test samples. For example, common parameters that are altered to provide unique scans on the same test sample include detection threshold percentage, waveform averaging, Normal and Difference gating options, an extensive gain setting range, and a multitude of pulser settings including pulse width which dictates the axial resolution. In terms of post-processing, the B-scan and 3-D view display methods are extremely useful from a qualitative standpoint, giving several options for observing the C-scan image data. The FFT tool is a solid option that can be useful for generating TOF values through cross-correlation. The RF waveform storage and replay is also very important for changing gates and other settings on the full set of A-scan

[*]Excel is a registered trademark of Microsoft Corp., Redmond, WA.
[†]SigmaPlot is a registered trademark of Systat, Inc., San Jose, CA.
[‡]Origin is a registered trademark of OriginLab Corporation, Northamption, MA.

data without physically re-running a scan. This is valuable for observing the A-scan data associated with the C-scan image map at a selected point for direct comparison.

The system capabilities are demonstrated with a 15-MHz ultrasound evaluation of an aluminum standard containing steps and drilled holes of different sizes and depths (figure 5). As shown in the image in the upper left corner of figure 5, the drilled holes in the first column increase in diameter and depth from top to bottom while the drilled holes in the second column decrease diameter and depth from top to bottom. This standard is useful for testing detectability limits of ultrasonic transducers with varying frequencies. A series of A-scans is exhibited over various regions of the sample to show the different reflected signals that can occur during point analysis evaluation (figure 6). The image to the right of each A-scan shows the transducer position over which the A-scan was collected. In figure 6a, a bulk region of the standard is selected to show top and bottom surface signals and their reflections. In contrast, the region in figure 6b is chosen to show signal changes during evaluation of one of the drilled holes. In this case, there are characteristic reflections from the holes and a corresponding reduction in amplitude of the bottom surface reflected signal. A-scan evaluations of the steps are shown in figures 6c, 6d, and 6e. In these A-scans, there is a TOF shift representing the change in distance from the transducer to the standard. The top and bottom surface reflected signals become closer together, exhibiting smaller TOF differences due to a shorter travel distance of the acoustic waves through the steps. In figure 7, B-scan and C-scan TOF images of the aluminum standard are shown. In the C-scan image, the TOF differences of the three steps vary in TOF compared to the upper platform. On the upper platform, four of the eight drilled holes are resolved, showing increased TOF values as the depths of the detected holes increase. The four drilled holes with the smallest diameters are

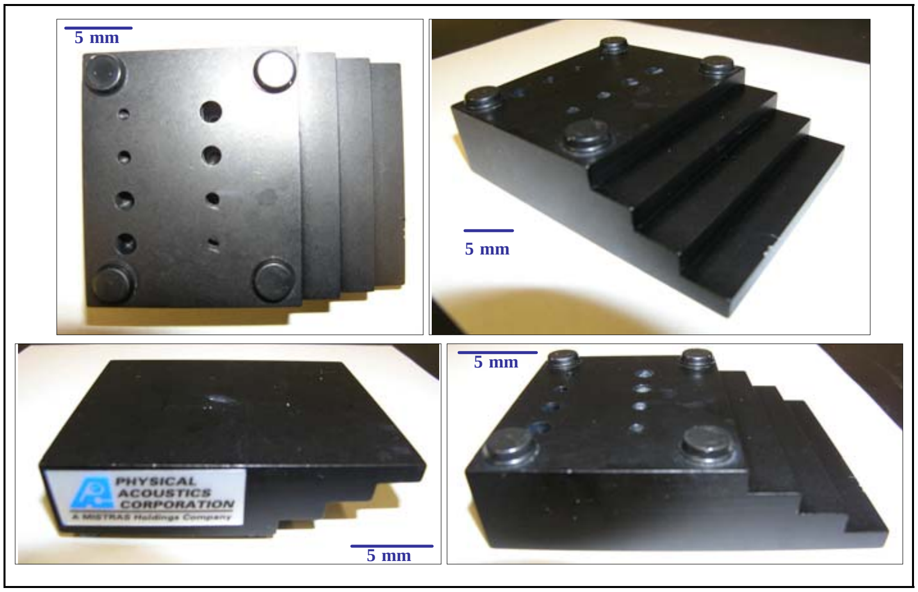


Figure 5. Aluminum standard sample featuring steps and drilled holes.

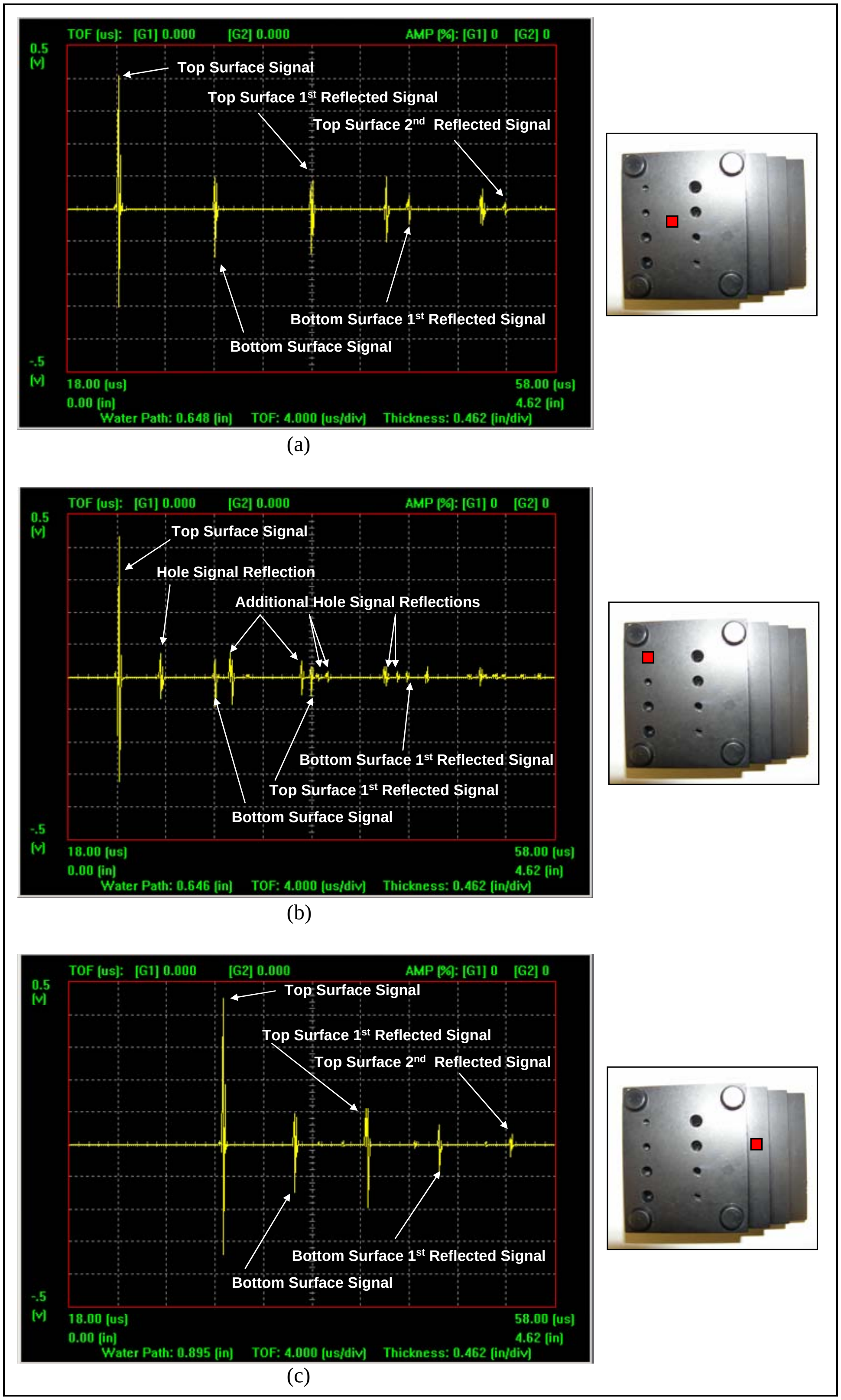
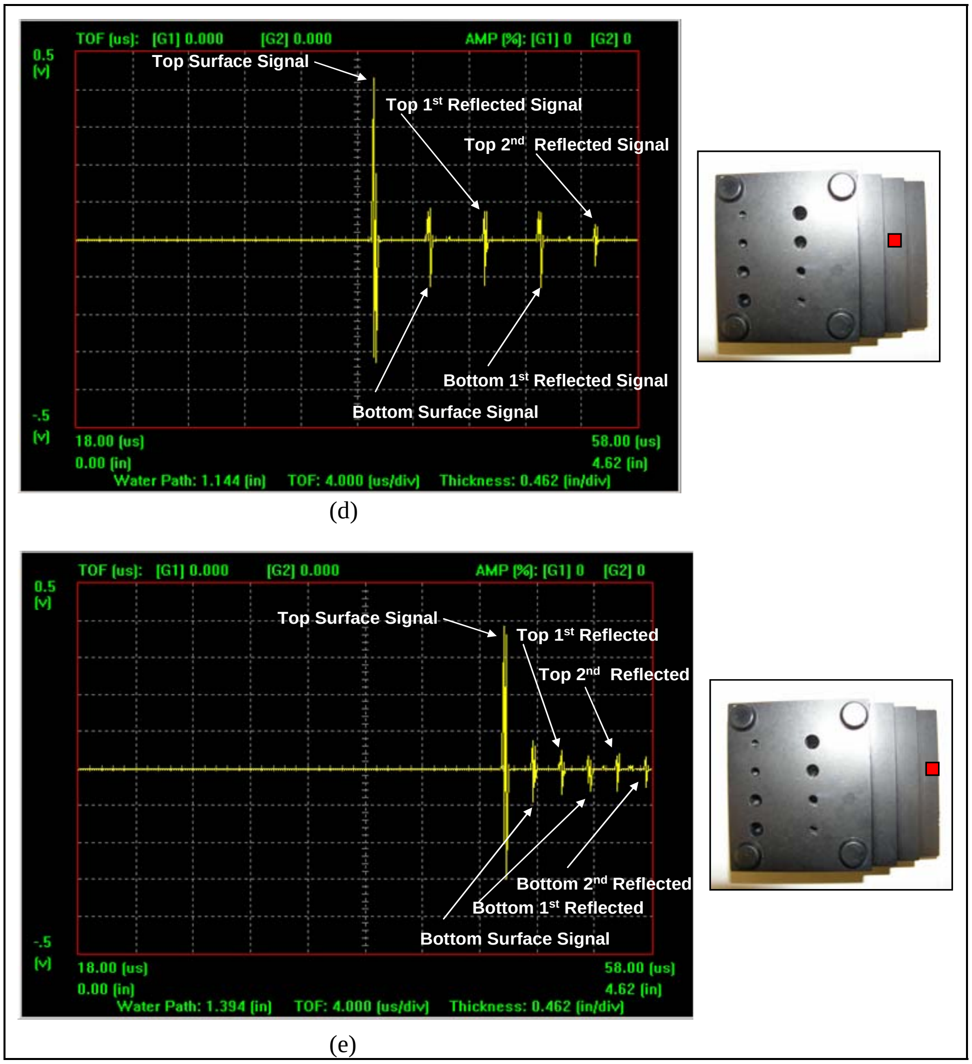


Figure 6. A-scan evaluation of aluminum standard at various positions.



(d)

(e)

Figure 6. A-scan evaluation of aluminum standard at various positions (continued).

not resolved by TOF C-scan imaging at 15 MHz. In addition to the drilled holes, there are also four circular regions of complete signal loss due to the presence of four rubber feet in the corners of the upper platform. The B-scan images show cross-sectional representations through horizontal and vertical lines selected from the C-scan image. The horizontal line intersects the steps, which increase in TOF from left to right as the transducer moves further away from the sample. This line also intersects the deepest drilled hole, which again corresponds to a high TOF value. The vertical line intersects two of the drilled holes, contrasting their depth and TOF values.

Figure 8 shows B-scan and C-scan AMP images. While the TOF images only detect four of the drilled holes, the AMP images are able to detect all eight, though the smaller diameter holes are more difficult to resolve at 15 MHz. The acoustic wave scattering that dictates the degree of attenuation is more sensitive to material inhomogeneties. A higher degree of attenuation

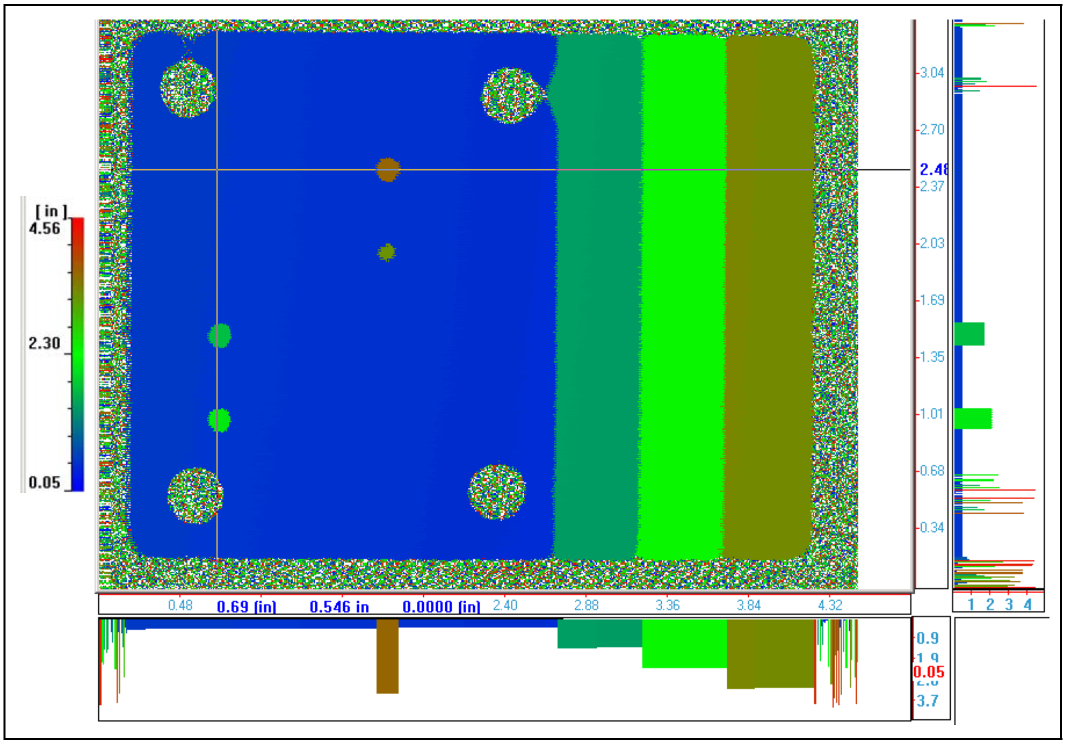


Figure 7. TOF B-scan and C-scan evaluations of aluminum standard.

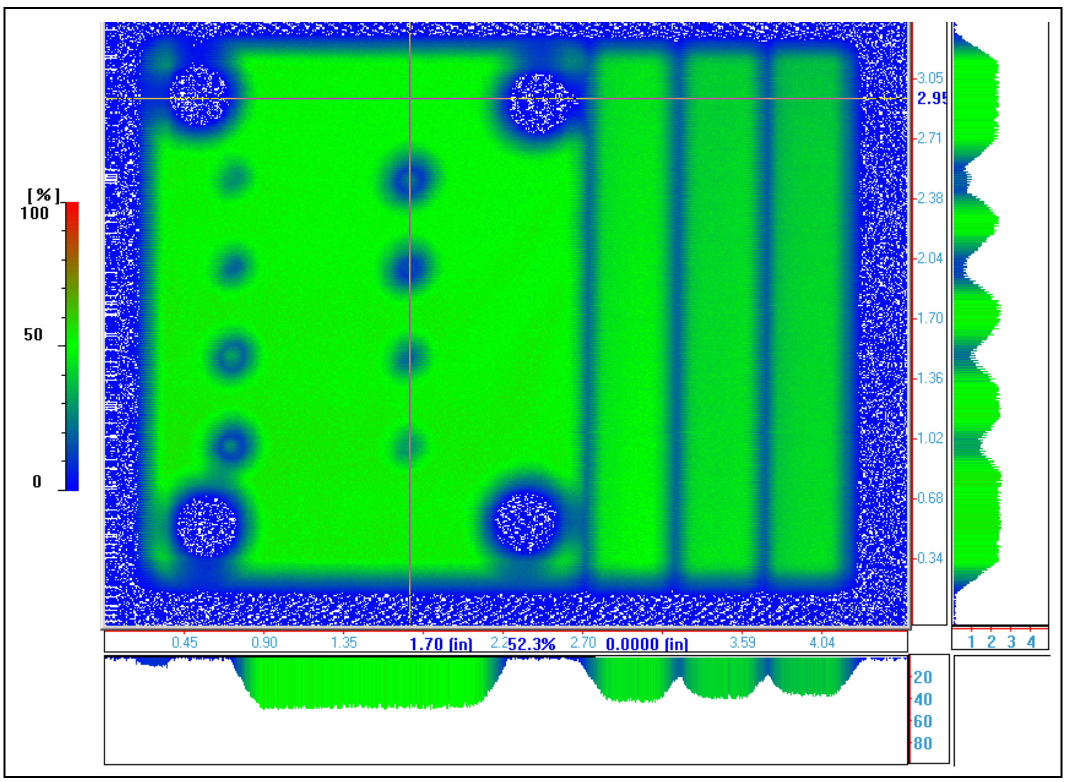


Figure 8. AMP B-scan and C-scan evaluations of aluminum standard.

corresponds to a lower bottom surface signal amplitude and these lower amplitude values are evident in the areas where the drilled holes are present (figure 8). However, unlike the TOF C-scan images, the AMP C-scan images are unable to provide the same amount of depth information for either the drilled holes or the steps in the standard. Some depth information is evident in the B-scan AMP images in which the depths of the holes and relative heights of the steps are observed through the cross-sections of the C-scan image. The horizontal line shows slight reductions in amplitude of the steps from left to right. The vertical line successfully demonstrates the trend of larger diameter and increasing depth from the top to the bottom of the sample. In figure 9, the culmination of the B-scan and C-scan images is utilized to construct a three-dimensional representation of the aluminum standard using the aforementioned 3-D post-processing function.

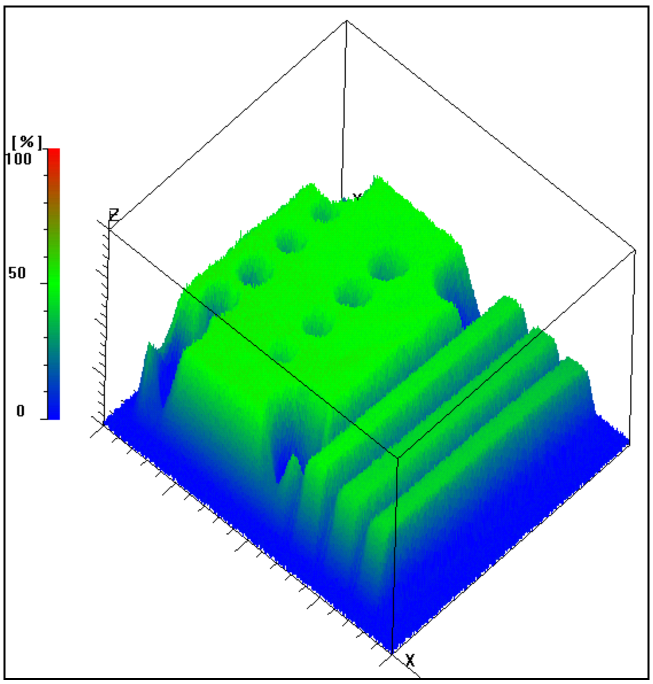


Figure 9. AMP 3D construction of aluminum standard.

In an additional test, the sample is flipped over to an orientation represented by the bottom left image in figure 5. However, instead of performing an evaluation at a single frequency, three different transducers with frequencies of 10, 15, and 20 MHz are used to contrast detectability. Figure 10 shows TOF scans and figure 11 shows AMP scans of the aluminum standard. In the TOF scans, as the frequency is increased, the drilled holes become more apparent. At 20 MHz, the size, shape, and depth are accurately represented in the C-scan image, while at lower frequencies the smaller diameter features are either undetected or only partially detected. For the AMP scans, the contrast between the bulk of the sample and the drilled holes increases with increasing frequency. At 20 MHz, all eight drilled holes are represented accurately in terms of diameter due to an improved detectability at the highest frequency. For evaluation of the

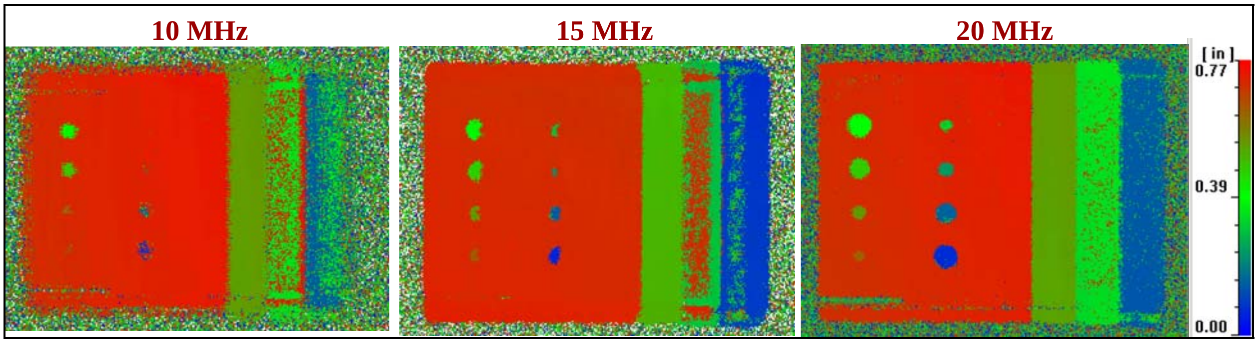


Figure 10. Transducer TOF frequency comparison of aluminum standard at 10, 15, and 20 MHz.

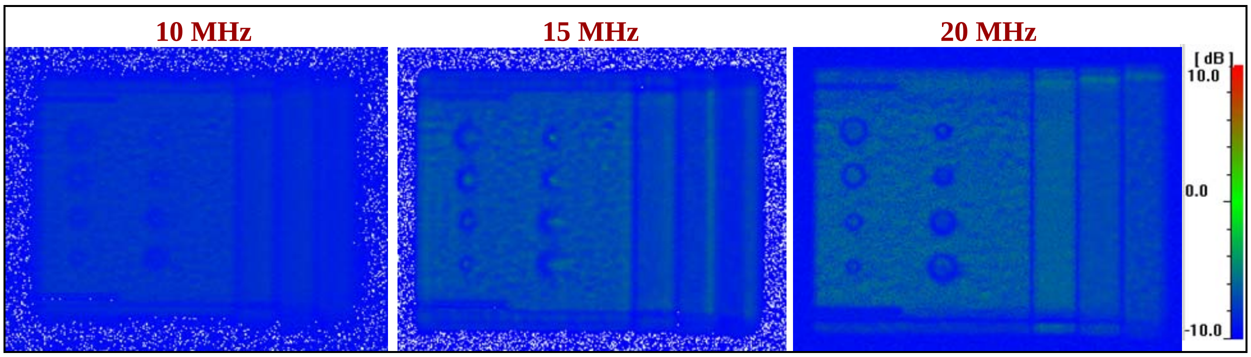


Figure 11. Transducer AMP frequency comparison of aluminum standard at 10, 15, and 20 MHz.

aluminum standard sample, the 20 MHz TOF and AMP scans provide the most detailed and accurate ultrasound analysis. Figures 6–11 give an example of some of the standard A-scan, B-scan, and C-scan ultrasound data that can be collected for evaluation of various test specimens.

While there are several positive features of the current ultrasound C-Scan imaging setup, there are also severe limitations. The first is the inability of the system to utilize transducers with frequencies higher than 20 MHz. Many of the new transducers acquired, as well as several of the older transducers, have frequencies much higher than 20 MHz, up to 100 MHz, and these cannot be utilized due to the current AD-IPR-1210 card. A severe limitation is the scan resolution capability of the software. The automatic maximum resolution option is the best choice for running any scan because it sets the optimum pixel size for a given area. By basing the maximum resolution on the size of the scan region, a larger sample can only be scanned at low resolution. However, when the resolution is manually set to a higher resolution than the automatic maximum resolution value, the resulting scan produces major processing errors and the image cannot be rendered properly. Without these glitches, this would not be an issue since manually setting a high resolution should increase the scan time due to collection of more data points but should not affect the integrity of the scan itself. It is the inability to use a resolution

below the automatic maximum resolution without experiencing errors that is the underlying problem. Another severe limitation is the inability to access the raw A-scan, B-scan, and C-scan image data, which prevents sufficient quantitative analysis. While qualitative analysis can be conducted by viewing the C-scan images, this option is limited to the range of TOF and AMP values set before the scan is run and cannot be altered to target specific values of interest. If the internal quantitative analysis package was strong or the raw data could be extracted, this would not be an issue. However, internal quantitative analysis is limited to cluster analysis, and the inability to extract raw data prevents transfer of x-position, y-position, AMP, and TOF data to a separate software package such as SigmaPlot or Origin, which are capable of performing extensive quantitative analysis. Since these issues are not only minor inconveniences but major limitations, there is a need for an additional system that can address these critical needs. At the minimum, an ideal system will have the capability of handling high frequency transducers, selecting a high resolution value without sacrificing the scan integrity, and collecting the raw C-scan data for proper quantitative analysis. This being said, the current system is sufficient for providing C-scan images, A-scan and B-scan data, flexible hardware options, and good qualitative capabilities with several unique features, but another system is necessary for full comprehensive ultrasound evaluation and quantitative analysis in order to conduct top level research.

5. Summary and Future Considerations

The current ultrasound system is an important tool for basic nondestructive evaluation. For more advanced evaluation and quantitative analysis, upgrading to a system with higher frequency, flexible resolution, and data extraction capabilities is necessary. While this paper is limited to describing standard systems for utilizing single element transducers and immersion scanning, comparatively newer technologies such as phased array and non-contact ultrasound are emerging. Non-contact, or air coupled, transducers have traditionally suffered from an inability to efficiently transmit acoustic waves through a medium of air. Air creates a large acoustic impedance mismatch with a majority of materials, causing a high degree of attenuation that is difficult to overcome. However, specialized transducers and signal processing methods are under development for providing increased sensitivity to reflected ultrasound signals. Non-contact ultrasound can eliminate the need for immersion of samples, especially those that are sensitive to water infiltration such as green ceramics.

Another technique is linear or phased array ultrasound. By increasing the number and reducing the size of transducer elements, a linear array or phased array transducer can be assembled. These smaller individual elements can be driven independently so that parameters such as array firing order, element selection, and pulse delay can be controlled. By pulsing elements simultaneously, depth of focus can be controlled for evaluating the test specimen at different

depths without changing the mechanical position of the transducer. Dynamic ultrasound beam control and steering can also be achieved by pulsing individual elements at slightly different times to control beam angle, focal distance, and focal spot size. Dynamic beam control is advantageous for inspecting components with complex shapes and for detecting defects of irregular shapes or multiple features along the perpendicular beam axis that would be difficult to detect using single element transduction. Electronic scanning can also be achieved using linear and phased array transducers by controlling the firing order of individual elements or groups of adjacent elements. This not only leads to faster inspection times, but also reduces the amount of mechanical transducer manipulation required for evaluating a large part. However, there are also disadvantages to utilizing phased array ultrasound. Since it is more difficult to fabricate the smaller elements that make up the linear and phased arrays, the cost is much higher than a single element transducer. With a large number of elements, there is a greater risk that the dimensions of the elements will vary slightly, increasing the degree of error involved since the frequencies and other parameters may change for different elements. Current linear and phased array transducers are incapable of achieving frequencies higher than 20–25 MHz, which limits the detection of defects. As the fabrication methods improve for producing specialized linear and phased array transducers, it is believed that the transducer frequencies will increase and the costs will be reduced. If this is achieved in the future, these transducers will be ideal due to their advantages of faster inspection times of complex parts at multiple angles and depths. These techniques will continue to be explored and implemented as technological advances are made. It is in this way that state-of-the-art ultrasound research can be achieved for successful nondestructive evaluation and quantitative analysis.

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